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Modeling Strongly Correlated Fermi Systems Using Ultra-Cold Atoms

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14. ABSTRACT
This report describes the successful construction of a system which will be used for investigations of 1D Fermi gases and the 2D Hubbard model. An entirely new apparatus was constructed that is capable of rapidly producing quantum degenerate Fermi gases. This work resulted in the development of a new all-solid-state laser source for red laser light which can be used for lithium spectroscopy and may be useful in other applications such as color displays, photodynamic therapy, and as a pump for Cr:LiSAF lasers. This work also led to new insights into how high-power multi-longitudinal mode fiber lasers can be used for preparing quantum degenerate atomic gases. Finally, a method for preparing Fermi gases in an optical lattice at exceptionally low temperature was proposed. The low temperatures attainable with this technique will permit exploration of the 2D Hubbard model's phase diagram in a regime where d-wave-paired superfluidity may be expected. Future experiments made possible by results of this work should give us new insights into electron transport in nanowires and the mechanism for high-temperature superconductivity in cuprate materials.

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I. Objectives

The goal of this research program has been to study condensed matter phenomena of interest in the development of new electronic devices. Specifically, an experimental system would be constructed capable of (1) investigating transport phenomena of spin-1/2 fermions in nanotubes made of light and (2) determining the phase diagram of the two-dimensional Hubbard model on a square lattice (a model which is purported to describe the high-temperature superconducting cuprates). A critical prerequisite for these studies is the achievement of temperatures below the Fermi temperature in a gas of neutral fermionic atoms.

II. Status

During the grant/contract period (May 15 2005 – November 30, 2007), we constructed a laser cooling and trapping apparatus for the confinement of neutral ^{6}Li atoms, attained quantum degenerate samples of ^{6}Li by evaporative cooling in an optical trap, developed a new all-solid-state laser source for red light and devised a method to prepare degenerate Fermi gases in an optical lattice at exceptionally low temperatures – low enough to observe d-wave pairing in the 2D Hubbard model if it exists. The experimental apparatus is now capable of investigations of 1D Fermi gases and the 2D Hubbard model. Such investigations may yield new insights into electron transport in nanowires and the mechanism for high-temperature superconductivity in cuprate materials.

III. Accomplishments/New Findings

A Source for Cold Fermionic Lithium Atoms

In the first full year of funding (December 1, 2005 – November 30, 2006), we completed construction of an apparatus for trapping and cooling of fermionic lithium atoms. The centerpiece of the experiment is an ultra-high vacuum system capable of achieving pressures ~10^{-11} Torr in the region where the atoms will be trapped (see Figure 1 below).

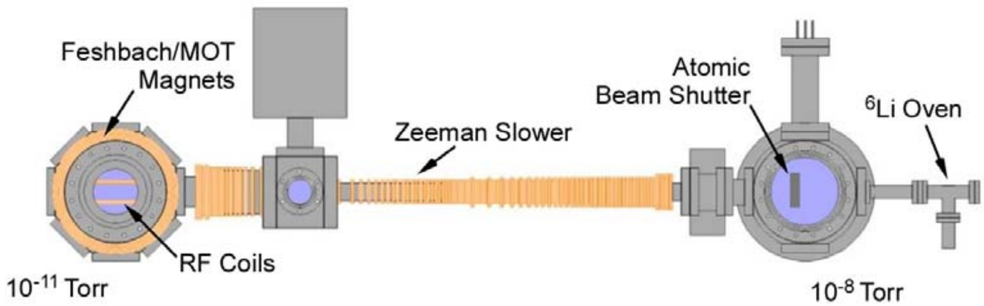

Figure 1. Overview of the UHV System. An atomic beam of lithium atoms (moving from right to left in the figure above) is cooled over the length of the "Zeeman Slower" and trapped in the region on the left hand side of the figure which achieves ~10^{-11} Torr.

Notable features of the apparatus include (1) high-field electromagnets capable of accessing several Feshbach resonances in ultra-cold lithium gases, (2) high-power, UHV-compatible, RF antennas mounted inside the vacuum system capable of driving rapid spin-flip transitions, (3) a high-flux atomic source, (4) high-resolution imaging from 2 orthogonal directions, and (5) substantial optical access for transmitting numerous optical lattice beams, dipole trapping beams and diagnostic laser beams. The system is capable of loading 10^9 ^{6}Li atoms into a magneto-optical trap (MOT) in 1 second. We can achieve peak densities of 10^{11} atoms/cc and temperatures as low as 200 μK in the MOT (note that lithium does not experience polarization gradient cooling resulting in

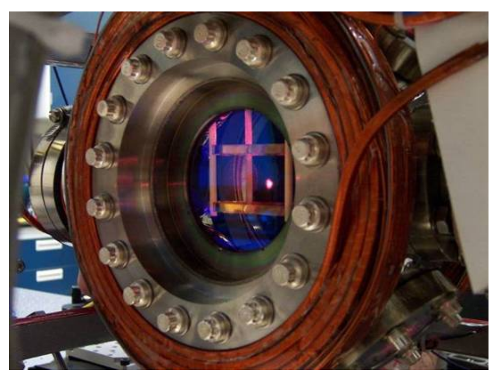

Figure 2. Magneto-Optical Trap. A cloud of 10^9 ^{6}Li atoms trapped in the center of the vacuum system are clearly visible to the naked eye as they rapidly scatter 671 nm photons from the trapping laser beams.

temperatures comparable to the Doppler limit as opposed to the recoil limit). An image of ^{6}Li atoms trapped in the MOT is shown in Figure 2.

New Discoveries in the use of High-Power Fiber Lasers for Atom Trapping

Ultimately, we will produce degenerate Fermi gases by evaporative cooling in a crossed-dipole trap. The crossed-dipole trapping configuration will provide an approximately spherical density distribution well-suited for loading atoms into a three-dimensional optical lattice. To produce this trap, we purchased a high-power (100 Watt) fiber laser operating at a wavelength of 1064 nm. A notable property of this laser is that it is a multi-longitudinal mode laser (producing a multi-frequency output). Single frequency fiber lasers which provide this power level are not yet commercially available. Several other groups around the world have recently purchased similar laser systems for trapping atoms. Our investigations have shown that, due to the multi-frequency output, one must take special precautions when designing the trapping geometry.

Our initial experiments with the fiber laser involved trapping atoms in a crossed-beam geometry. The output of the fiber laser was split into two equal power beams which were each separately focused and made to intersect at an angle of 90 degrees. **Error! Reference source not found.** shows an absorption image of lithium atoms loaded from the MOT into the crossed dipole trapping potential. Initially, the two beams forming the trap had parallel linear polarizations. We found, however, that in this configuration the trap had an extremely short lifetime ~30 ms. The decay was exponential, indicating a single-body loss mechanism. With the low pressures we achieve in our vacuum system, we expected a much longer lifetime (10s to 100s of seconds). We also measured the intensity and position noise power spectra for the beams forming the trap and found these

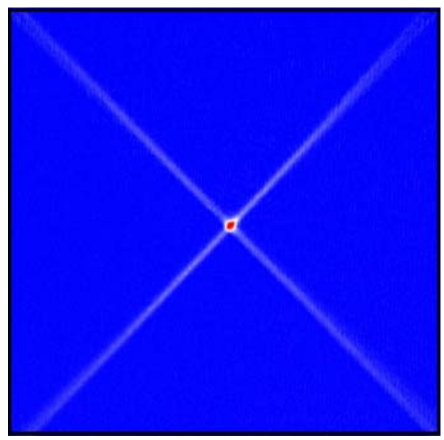

Figure 3. Atoms Loaded into a Crossed Dipole Trap. An absorption image of atoms loaded into a crossed dipole trap formed at the intersection of two focused laser beams. The image was recorded a few milliseconds after the trap was loaded from the MOT. The majority of atoms are confined at the intersection of the two beams.

to be sufficiently small to expect long lifetimes. Thus, the observed short lifetime was a bit of a mystery.

A possible culprit for loss mechanisms in this trap is the multi-frequency nature of the fiber laser's output. Based on the length of the fiber laser cavity (estimated by IPG Photonics, the manufacturer of the laser) we expect that the longitudinal mode spacing is 7 MHz ±1 MHz. With such a closely spaced spectrum of lines, it is possible that when this laser is used in a crossed beam configuration it drives a two-photon Raman transition between bound and free states of the trapping potential. The two photons driving this transition are from different longitudinal modes of the laser and have different wave vectors (i.e. one photon is coming from each beam that forms the crossed trap). In order to drive bound-to-free transitions of the trapping potential, the photons driving the transition must have different wave vectors. We tested this hypothesis by two methods: (1) using crossed linear polarizations for the trapping beams and (2) stroboscopically alternating the beams very rapidly (~100 kHz) such that the beams were never on simultaneously (the atoms experience a time-averaged-potential if the modulation frequency is much greater than the oscillation frequency for atoms in the trap). We expected that the use of crossed linear polarizations would increase the lifetime due to the fact that the Raman Rabi frequency goes to zero in the limit of large detuning with respect to the fine structure splitting of the atoms. The stroboscopic technique was expected to increase the lifetime due to the fact that photons with different wave vectors would never be present simultaneously. In both cases, the lifetime was, in fact, increased dramatically to 4 seconds. We later found that this 4 second lifetime was most likely limited by collisions with a background Li vapor from the high-flux atomic beam (see below).

From these observations we are now in a position to properly design a crossed-dipole trap produced by the multi-mode fiber laser that will store atoms for a long time (10s of seconds) with negligible heating. By using trapping beams with crossed linear polarization and stroboscopically alternating the beams, we will be able to significantly extend the trap lifetime. We are currently in the process of reconfiguring the optics so that we will be able to stroboscopically alternate the beams and still maintain a large well depth.

Achievement of Temperatures below the Fermi Temperature

As a proof-of-principle experiment to verify that our system was capable of achieving quantum degeneracy and to determine the fundamental limit on our trap lifetime, we decided to trap atoms in a tightly focused, single-beam dipole trap using light from a 50 Watt single-frequency fiber laser (1064 nm). This laser was originally purchased to provide optical lattice beams for our experiment and will ultimately be used for this purpose. In the process of diagnosing our system, however, it was useful to use this laser to form a single-beam trap since it would not suffer from the complications we found with the multi-mode laser.

To form the trap, a single-beam is focused to a waist radius of 22 μm which has a corresponding Rayleigh length of 1.4 mm. For 45 Watts of incident laser power, the trap depth is 3.6 milliKelvin.

We were somewhat surprised to find that our trap lifetime in the single beam trap was also limited to ~4 seconds but soon discovered that the loss was being caused by collisions with atoms in a background lithium vapor produced by our high-flux atomic

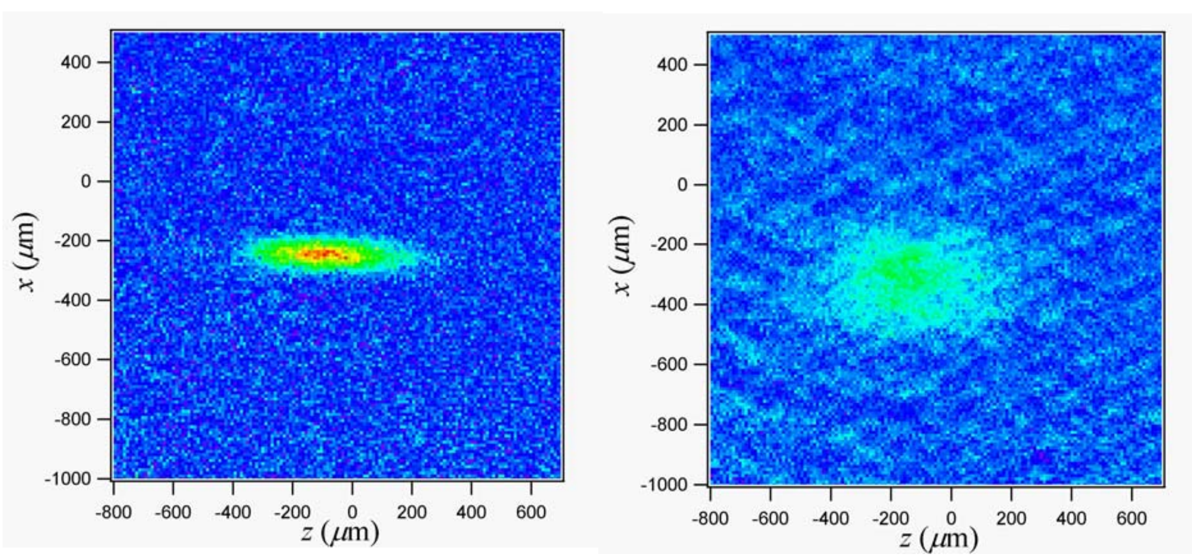

Figure 4. Achievement of Temperatures below the Fermi Temperature. Time-of-Flight absorption images of 8×10^4 atoms released from the single-beam, dipole trap after evaporative cooling. The figure on the left (right) shows the distribution after 800 μs (2.8 ms) of free expansion. Analysis based on Boltzmann statistics indicates that the temperature of the cloud T = 1 μK, approximately half of the Fermi temperature (T_F = 2 μK) of the trapped gas.

beam. By substantially reducing the time it takes to load atoms from the atomic beam into our MOT, we were able to shield the UHV region from the oven region by using an atomic beam shutter installed inside our vacuum system (see Figure 1). By keeping this shutter closed for the majority of the experimental sequence, we were able to increase our trap lifetime to >40 seconds.

Although the number of atoms loaded into the single beam trap is somewhat small ($<10^6$ atoms), we have been able to demonstrate evaporative cooling of the gas to temperatures below the Fermi temperature. In these experiments, a spin-mixture of ^{6}Li atoms is prepared in the two lowest energy hyperfine states by optical pumping. A bias magnetic field of 300 Gauss is then applied to increase the scattering length for atoms in different spin states to -300 a_0. With such a large elastic cross section and negligible loss, the atoms could quickly rethermalize in the trap. Forced evaporative cooling was accomplished by slowly reducing the depth of the optical trap by a factor of 100 over six seconds. After evaporation, we achieve temperatures $T \approx 0.5\ T_F$ with $8\text{x}10^4$ atoms remaining. This demonstrates that our experimental system is capable of rapidly producing quantum degenerate Fermi gases.

Construction of a High-Flux Source of Highly-Degenerate, Fermionic Atoms

Having successfully attained temperatures below the Fermi temperature in our system, we are currently improving upon our trapping and cooling techniques so that we may produce very large, highly-degenerate Fermi gases at an unprecedented production rate. This high-flux source of Fermi gases will allow us to achieve the high signal-to-noise ratios that are required for our planned experiments on the quantum simulation of the Hubbard model. Our new technique for rapidly producing large Fermi gases relies on (1) using a large-volume, magnetic trap to compress the atomic gas to a volume that can be captured by an optical trap and (2) employing optical cooling techniques in an optical lattice to achieve temperatures close to the Fermi temperature with only a small loss of atoms.

Production of large, highly-degenerate ^{6}Li gases will be accomplished using the procedure shown schematically in Figure 5. Atoms are first loaded from a MOT into a spherical quadrupole trap which will be used to compress the atoms into a small volume by increasing the field gradient to a maximum strength of 500 Gauss/cm in <100 ms. At this point, the density of atoms will be 7×10^{11} atoms/cc at a temperature of approximately 800 μK.

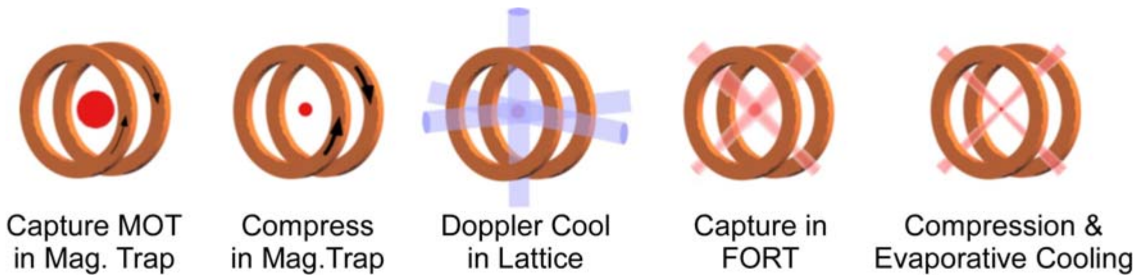

Figure 5. High-flux source of quantum degenerate fermions. The illustration above shows our proposed steps (from left to right) for the rapid production of very large Fermi gases. We will initially capture nearly all of the atoms from our MOT in a spherical-quadrupole magnetic trap. The atomic cloud will then be compressed to a small volume in the magnetic trap. The atoms, which have been heated by compression, are captured in an optical lattice, cooled with the optical molasses beams, and adiabatically released from the lattice into a crossed-dipole trap. The crossed dipole trap is compressed and forced evaporative cooling is accomplished by adiabatically lowering the well depth.

The atoms will then be loaded into a blue detuned, near-resonant, optical lattice in which they will be cooled by applying optical molasses beams. The optical lattice consists of three 500 mW retroreflected beams, each focused to a 500 μm waist spot size (at the location of the atoms) and detuned 10 GHz to the blue of resonance. We estimate that the lattice should capture ~10^8 atoms. Light for this lattice is provided by a custom-built, frequency-doubled, diode-pumped solid-state laser for 671 nm light (described below). The lattice has a maximum depth of 3.5 mK and a peak photon scattering rate of 11 kHz. The oscillation frequency at each site of the lattice is $\nu = 4.6$ MHz. Simple Doppler cooling of the atoms in the lattice can thus cool atoms such that they only significantly populate the first two vibrational levels. It has been shown that the detrimental effects of radiation rescattering in a dense cloud can be avoided by ensuring that the atoms are in the *festina lente* regime (where the oscillation frequency $\omega_0 = 2\pi\nu$ far exceeds the optical scattering rate Γ_{sc}). For the lattice described above, the Lamb Dicke parameter $E_R/h\nu = 0.12$ and the *festina lente* criterion $\Gamma_{sc}/\omega_0 = 0.03 << 1$ is well satisfied even when Doppler cooling light is applied. Doppler cooling occurs rapidly and can be implemented in <5 ms. Following Doppler cooling in the lattice, atoms will be optically pumped into the F=3/2, m_F = 3/2 state and adiabatically released from the lattice back into a weak magnetic trap for additional compression. Note that during adiabatic release the bulk density (the density averaged over multiple lattice sites) remains fixed while the temperature is dramatically reduced. We anticipate that the temperature following release will be less than 35 μK (i.e. 10 times the recoil temperature).

Repetition of this sequence of compression in a magnetic trap (<100ms), optical cooling in a lattice (<5ms) and adiabatic release from the lattice (<100 μs) can ultimately provide gases at a density of half the lattice site density and a temperature of less than 35 μK. Thus, using this technique we expect to rapidly produce a gas of ~10^8 atoms at a density of 1.3 x 10^{13} atoms/cc and a temperature of 35 μK which corresponds to a phase space density ρ = 1/45. A final compression step in the magnetic trap can be used to increase the density to 5 x 10^{13} atoms/cc and a radius of ~50 μm with a corresponding increase in temperature to 89 μK for optimal mode matching to the crossed dipole trap described above.

Ultimately, degenerate samples will be prepared by rapid forced evaporative cooling of a two spin-state mixture of ^{6}Li atoms from the crossed dipole trap. For beams focused to 100 μm waist diameter, this trap can provide a depth of 170 μK along its weakest direction. Thus we expect a very large fraction of the atoms available from the final compression stage in the magnetic trap to be transferred to the optical trap. Since these atoms are already at a phase space density of 1/45, only a modest amount of evaporative cooling is required. For evaporative cooling and the remainder of the experiments, atoms will be optically pumped into the lowest energy spin states (corresponding to F=1/2, m_F = ±1/2). A 50/50 spin mixture will be created using RF fields, and rapid evaporative cooling can be achieved using the Feshbach resonance at 834 Gauss. This final stage of evaporative cooling should only require ~1 sec. In this way, highly-degenerate samples of >10^7 lithium fermions (comparable to the largest degenerate Fermi gases ever attained) can be produced once every few seconds. This would be the highest flux source of degenerate Fermi gases in the world, by more than an order of magnitude.

The spherical quadrupole magnets required to implement this technique have been constructed and, as described below, the solid-state laser source required for the lattice is now operational.

A Single-Frequency, High-Power, Solid-State Laser Source at 671 nm

The high-flux source of degenerate lithium fermions described above critically depends on the availability of a high-power (~1.5 Watt) tunable laser source of 671 nm light to provide the near-resonant optical lattice. Currently, the only available commercial options for producing tunable 671 nm radiation are dye laser systems (which are costly and notoriously difficult to stabilize) and diode laser systems (which are limited to 350 mW of power at 671 nm).

We are developing an all-solid-state laser source for 671 nm light (see Figure 6) which has the potential for producing multiple Watts of power with very good frequency and power stability. The all-solid-state laser source we have constructed is a diode-pumped Nd:YVO_4 laser operating at 1342 nm. This laser will be frequency doubled to produce 671 nm radiation. The frequency doubling will be accomplished by passing light through a periodically-poled lithium niobate crystal that is mounted inside a power build-up cavity. Due to the all-solid-state construction, this laser system can be made to be highly stable, both with regard to frequency and power fluctuations. Furthermore, the laser system can be easily scaled up to very high power levels by employing power amplifiers at 1342 nm.

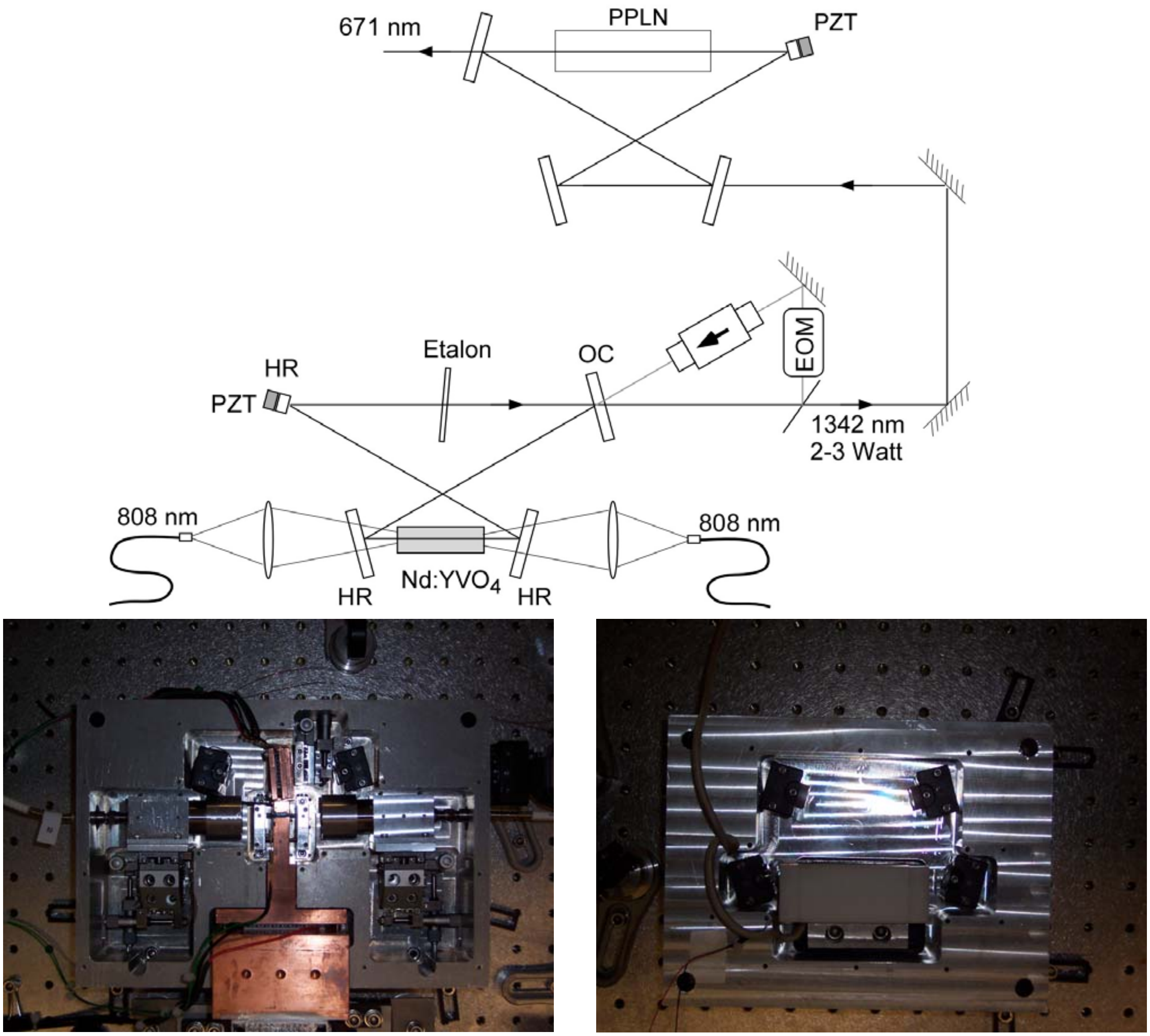

Figure 6. All-solid-state laser source for 671 nm light. The uppermost figure is a schematic diagram of the new 671 nm laser source we have constructed. The laser source consists of a diode-pumped Nd:YVO_4 laser operating at 1342 nm which is frequency doubled by a periodically-poled lithium niobate crystal that is placed inside a power build-up cavity. We have generated up to 6 Watts of light at 1342 nm. The lowermost figure shows the completed 1342 nm tunable laser and frequency doubling cavity. Ultimately, this laser system will provide a powerful, highly stable source of 671 nm laser light that can be used for magneto-optical trapping beams and optical lattice beams in our experiment.

We believe that the development of this laser will give our experiment a technological edge by providing a relatively inexpensive, high-power and stable source for 671 nm light. The high-flux source described above is a perfect example of the technical advantage this laser makes possible. In this case, the deep optical lattice that will be used to capture nearly all of the atoms in the MOT for laser cooling requires the availability of such a source. Eventually, we plan to build a second laser system to replace a dye laser system we currently use in our experiments. By upgrading this laser system to an all-solid-state laser source, we expect to achieve high stability in our experiments since all of the laser beams used in our apparatus would then be derived from solid state sources.

The high-brightness, 671 nm laser source we are developing also has potential applications beyond laser cooling and trapping of lithium atoms. Compact, all-solid-state, high-brightness sources of 671 nm radiation are of interest for use in color laser displays, medical treatment (e.g. photodynamic therapy), and as a pump laser for tunable Cr^{3+} lasers. This high-performance, all-solid-state laser can be a replacement for inefficient krypton-ion lasers. Furthermore, the high-power output at 671 nm can be frequency doubled to provide a compact, tunable source of light near 335 nm.

Preparing a Fermi Gas in an Optical Lattice at Ultra-Low Temperature

A primary challenge for performing quantum computation and simulation with neutral atoms in an optical lattice is the requirement for extremely low temperatures (or equivalently, zero entropy). Initialization of the quantum register for quantum computations requires a gas of neutral atoms in a near-zero-entropy state. Similarly, quantum simulation will require extremely low temperatures so that thermal fluctuations do not overwhelm the weak spin-spin interactions between atoms in the lattice. Quantum simulation of the Hubbard model, for example, will require unprecedented low temperatures to access the exotic phases that may be observed in this system (e.g. antiferromagnetism and *d*-wave superfluidity). Our group has proposed a procedure for preparing fermionic atoms in an optical lattice at temperatures $T \sim 0.001\ T_F$.

The proposed scheme is depicted in Figure 7. (For clarity, we will present the approach assuming that we load a single-component Fermi gas into the lattice. In practice, we will implement the procedure with a two-component gas.) We begin by loading atoms in a lattice at an average density greater than 1 atom per lattice site. Due to the exclusion principle, atoms are forced to populate energy levels in the second band. Assuming that the gas is reasonably cold to begin with (i.e. $T \sim 0.1\ T_F$), the occupation number for only those states which are within $k_B\, T$ of the Fermi surface (which is in the second band) differ appreciably from unity. Thus, atoms fill the first band with near unit occupancy and only the second band has appreciable holes in the Fermi sea. The atoms in the second band can then be selectively removed by intensity modulation of the lattice beams. Intensity modulation can selectively drive 2nd to 4th band transitions while avoiding 1st to 3rd band transitions if the lattice depth is approximately 35 E_R or greater. (The 1st to 3rd band and 2nd to 4th band transition frequencies become resolvable at around 35 E_R.) Once atoms have been selectively transferred to the 4th band, they can be allowed to escape the trapping potential by reducing the lattice potential. With the atoms in the 2nd band now having been removed, one is left with atoms occupying all of the energies levels in the first band with near unit occupancy. In this way, a near-zero-temperature Fermi distribution with exactly one atom per lattice site is produced.

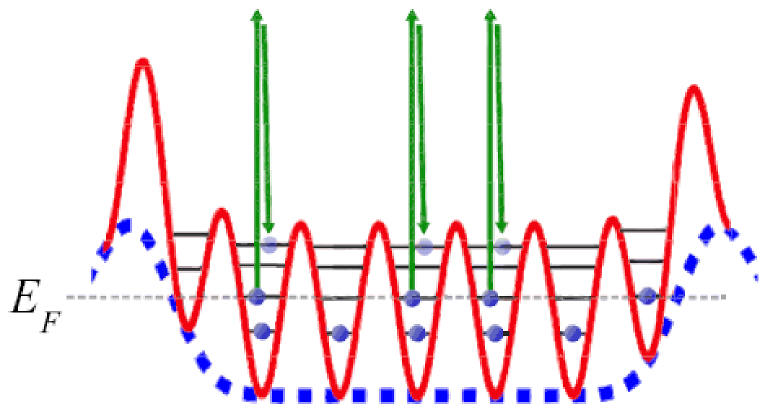

Figure 7. Scheme for preparing a near-zero-temperature Fermi gas. Initially, atoms at a density greater than 1 atom per lattice site and a temperature $T \sim 0.1\ T_F$ are loaded into an optical lattice. The occupation number for states in the first band is very close to unity, whereas the occupation number for states near the Fermi surface in the second band can be less than unity. A near-zero-entropy state is prepared by selectively removing atoms in the second band from the lattice potential.

In practice, this technique will be implemented with a two-state mixture of fermionic atoms. Thus, a near-zero-temperature Fermi distribution with two atoms per lattice site (one spin-up and one spin-down) will be produced. This will take place in a 3D cubic lattice formed from 1064 nm laser beams. To create a lattice at half-filling (one atom per site either spin-up or spin-down), a 532 nm laser beam will be applied along one axis of the lattice and will be retro-reflected off of the same mirror used to retro-reflect the 1064 nm light for that lattice (so that they are robustly phase stable). This 532 nm lattice beam will be adiabatically applied to coherently split each lattice site in two and thereby realize a lattice at exactly half filling.

In the qualitative description above, we assumed that external confinement is provided by a "box" potential. This situation is not experimentally realistic. In fact, optical lattice experiments have typically relied on an external harmonic potential to ultimately provide confinement of the atoms. We have numerically modeled the process described above using externally confining potentials that we can realistically produce. We expected, and numerical modeling has confirmed, that the closest approximation to a box-like potential that we could devise would result in the lowest achievable temperatures.

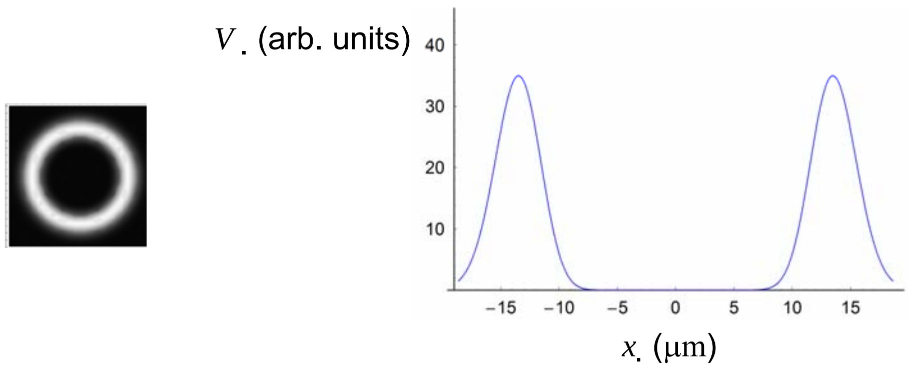

Figure 8. Laguerre-Gaussian Trap . (Left) A 2D cross section of a Laguerre-Gaussian laser beam. Atoms will be confined in the dark central region. (Right) A 1D radial profile of the Laguerre-Gaussian beam we used in our model of filter cooling.

We will experimentally realize a box-like potential for atoms by using a hollow, blue-detuned Laguerre-Gaussian (LG) laser beam. The cross section and potential produced by a 12th order LG beam are shown in Figure 8. An LG beam is a propagating mode of an electromagnetic wave that has a dark center. For light blue-detuned from atomic resonance, atoms are repelled from regions of high intensity. The use of a high-order LG laser beam allows the walls of the potential to be relatively sharp. We will intersect two LG beams to generate a box-like potential in 3D.

We have modeled the process of adiabatically loading atoms into the lattice taking into account the LG beam profiles that will be used for external confinement and a full three-dimensional lattice. The entropy as a function of temperature was calculated for various lattice depths and is shown in Figure 9. In contrast to the behavior seen in the case of harmonic confinement, the atoms are adiabatically cooled to very low temperatures when loaded into the lattice. The process of selectively removing atoms from the second band cools the atoms further (assuming the atoms rethermalize via collisions). Figure 10 shows the final temperature of atoms in the lattice following both the process of loading and selective removal of atoms in the second band. This is plotted as a function of initial atom number. The minimum achievable temperature predicted is $T \sim 0.003\ T_F$. Achieving this temperature only requires a modest reduction in the number of atoms (of about 12%). Furthermore, Figure 10 indicates that the cooling scheme can be robust against initial number fluctuations of ±10% (typical fluctuations in these experiments).

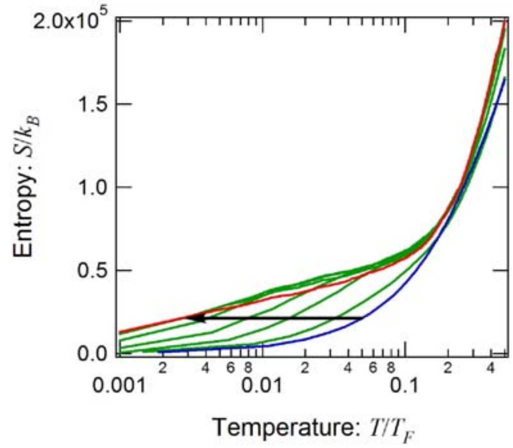

Figure 9. Adiabatic Loading of a 3D Lattice. The entropy as a function of temperature is shown for several lattice depths from 0 E_R (blue) to 35 E_R (red). Adiabatic loading maintains a constant entropy. Starting from T_i = 0.05 T_F, the gas is cooled to T_f = 0.003 T_F.

This scheme provides a technique for achieving temperatures $T \sim 0.003\ T_F$ at exactly half-filling and only a modest reduction in the number of atoms. We will also be interest in quantum simulation of the Hubbard model away from half-filling. In this case, the LG beam will be adiabatically expanded using a zoom lens when the lattice is at a depth that allows the atoms to expand by tunneling. This will be a powerful technique for preparing the system for studies of phases of interest at half filling as well as away from half filling. The results of this work have been submitted for publication in *Physical Review Letters.*

We are currently working on implementing this cooling procedure in our laboratory. We have generated LG beams using a vortex phase plate. We will also investigate generating the LG beams using diffractive optics that we are fabricating at Penn State's Nanofabrication facility.

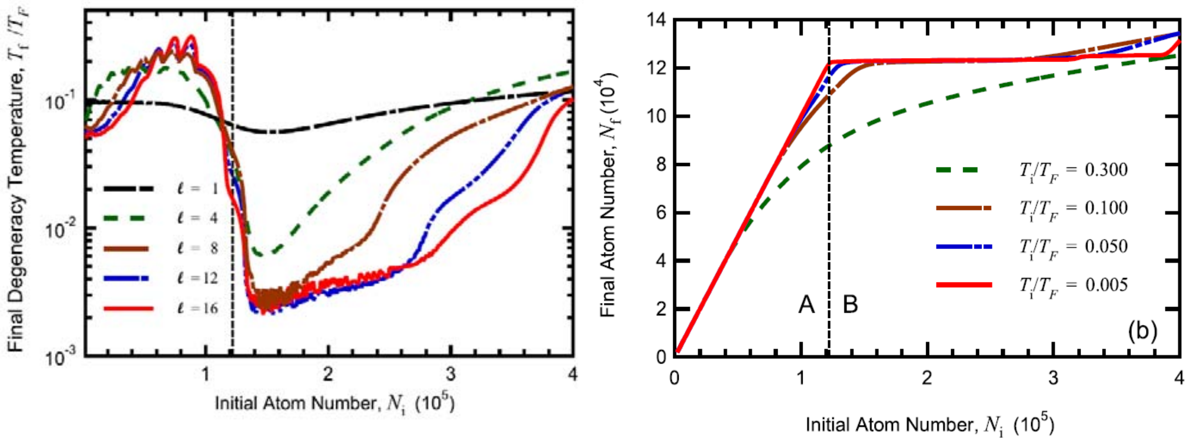

Figure 10. Final Temperature and Atom Number after Filtering. (left) The final temperature that the gas will rethermalize to after atoms in the second band are removed is shown as a function of the initial number of atoms used in the model. The different color curves are for different charges l of the Laguerre-Gaussian laser beam. The higher the charge, the more "box-like" the potential. (right) The final atom number that remain after filtering. Note that in the regime where low temperatures are achieved, fluctuations in the initial atom number are dramatically reduced.

IV. Personnel Supported

The research staff working on this project consists of:

Principle Investigator:	Prof. Kenneth M. O’Hara
Postdoctoral Associate:	Dr. John H. Huckans
Graduate Student:	Jason R. Williams
Graduate Student:	Ronald Stites
Graduate Student:	Eric Hazlett
Senior Technologist:	Thomas Essinger-Hileman
Undergraduate Student:	Bradley Cochran
Undergraduate Student:	Kristina Calloday

Salaries for the research staff were paid in part from startup funds provided by Penn State. This allowed the majority of funds from the AFOSR to be used to purchase equipment required for construction of the experimental apparatus.

V. Publications

“Preparing a highly degenerate Fermi gas in an optical lattice,” J. R. Williams, J. H. Huckans, R. W. Stites, E. L. Hazlett, and K. M. O'Hara, submitted to *Phys. Rev. Lett.*, preprint available at arXiv:0804.2915

VI. Interactions/Transitions

Presentations at Meetings, Conferences, Seminars

“Progress Toward Realization of the 2D Hubbard Model,” J. R. Williams, R. Stites, , J. H. Huckans, and K. M. O’Hara, Poster Presentation, Annual Meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP), Knoxville, TN (May 17, 2006).

“Preparing Fermions in an Optical Lattice at Ultra-Low Temperature,” J.R. Williams, R. Stites, J.H. Huckans, E.L. Hazlett and K.M. O'Hara, Oral Presentation, Annual

Meeting of the Division of Atomic, Molecular and Optical Physics (DAMOP), Calgary (June 7, 2007).

"Quantum Bits, Quantum Magnetism and Superconductivity: The Exotic World of Fermionic Atoms in an Optical Lattice," University of Delaware, Atomic, Molecular and Optical Physics Seminar (November 19, 2007).

"Quantum Simulation of the Hubbard Model using Ultra-Cold Atoms," Regoupement Qubcois sur les Materiaux de Pointe (RQMP), RQMP Summer School, Orford Quebec Canada (August 3, 2007).

"Realizing the 2D Hubbard model using 6Li," The Canadian Institute for Advanced Research, Workshop on Quantum Simulation, Vancouver, British Colombia Canada (February 2007).

VII. New discoveries, inventions, or patent disclosures.

None during this grant/contract period (Sept. 1, 2006 – August 31, 2007).

VIII. Honors/Awards

Presidential Early Career Award for Scientists and Engineers, June 2006.